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Sustainability governance of the Danish bioeconomy — the case of bioenergy and biomaterials from agriculture

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Abstract

Background: The EU bioeconomy strategy aims to accelerate the European bioeconomy and its contributions to the United Nations Sustainable Development Goals and the Paris Agreement. National policies and strategies in many countries promote their bioeconomies. The importance of agricultural crops and residues as raw materials for the bioeconomy is increasingly recognised, but agricultural production also contributes to large impacts on nature and environment. With the aim of assessing the governance measures and their effectiveness in addressing the sustainability of bioenergy and biofuel production, the purpose of this study was to map the governance complex relevant to agricultural crop production in Denmark, and to identify the achievements, challenges and lessons learned.

Methods: The analysis is based on a review and assessment of publicly available databases, inventory reports and scientific literature on governance measures and their effectiveness. Governance here includes a variety of legislation, agreements, conventions and standardisation. Environmental sustainability is represented by greenhouse gas emissions from the agricultural sector, soil carbon, water quality and biodiversity.

Results: The agricultural sector has a significant impact on Danish climate performance and on landscapes in the form of soil carbon losses, leaching of nutrients to water bodies and pressures on biodiversity. The governance complex addressing these issues is made up of a variety of state regulation and co-regulation between state and firms, state and NGOs, or NGOs and firms. Much regulation is adopted from EU directives and implemented nationally.

Conclusions: The analysis found that greenhouse gas emission is a virtually unregulated field and additional regulation is required to live up to Denmark's 2030 emission reduction targets. The regulatory framework for soil carbon is criticised for its complexity, its competing instruments and its recognition procedures of voluntary co-regulation. For water quality governance measures in place have improved water quality, but it is still difficult to achieve the goals of the Water Framework Directive. It remains a challenge to protect biodiversity in agriculture. Biodiversity is mainly governed by national and supranational regulation, but co-regulating between state and firms and NGOs and firms have been initiated in the framework of the Agricultural Agreement.

Keywords: Governance, Sustainability, Bioenergy, Biomass, Agriculture, GHG emissions, Soil carbon, Water quality, Biodiversity

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Background

The 2018 update of the EU bioeconomy strategy [1] aims to accelerate the European bioeconomy and its contributions to the United Nations Sustainable Development Goals (SDG) and the Paris Agreement. National policies and strategies in many countries also promote their bioeconomies. Bioeconomic development can transform a nation's economy through a number of pathways, i.e. through fossil fuel substitution; through technological innovation in primary production in agriculture, forestry and fishery or in the downstream processing industries; or through biotechnological industrial development [2]. Bioeconomic transformation through fossil fuel substitution has been stimulated in the EU through the renewable energy directive (RED) [3], and bioenergy and biofuels play a significant role in the European bioeconomy [4]. In ensuring that the bioeconomic transition is sustainable, the EU relies on public and private governance instruments [5, 6] and individual countries deploy different levels of enabling and constraining governance [2].

Agricultural crop production takes place throughout the globe, and the importance of agricultural crops and residues as raw materials for energy, chemicals, and the bioeconomy more generally, is increasingly recognised [7–10]. However, agricultural production has a large impact on nature and the environment [11]. Undesired impacts can for instance occur when lands of high biodiversity value or with high carbon stock are converted to agriculture. Other undesired impacts may occur due to use of pesticides and fertilisers, or by emission of greenhouse gases (GHG). Agricultural activities can reduce the environmental quality of the surrounding ecosystems and of the agricultural land itself.

Denmark is only a small part of the global bioeconomy, but it leads when it comes to the intensity of agricultural land use and production. The potential for conflicts that can only be resolved by regulation is high. About 62% of the land area is under agricultural management. At the same time Denmark has formed comparatively ambitious policies for a transition to renewable energy, including bioenergy [12], which are all policies that can increase pressure on land use and crop production systems. Agriculture has been comprehensively regulated for decades to reduce the environmental impact of crop and livestock production. However, several conflicts exist and new conflicts may arise with the increased focus on the bioeconomic transition [2]. Governance relevant to the Danish bioeconomy is made up of a mix of public and private regulation, voluntary and mandatory schemes, and national and supranational legislation. Altogether, this makes an important case for an analysis of the governance in place to ensure sustainability.

The overall aim of this study was to analyse the governance complex relevant to the environmental sustainability of bioenergy and biofuel production based on agricultural production, i.e. dedicated energy crop production and residue use. More specifically, the objectives were to (1) identify the achievements, challenges and lessons learned from historical and existing governance of the sustainability of agricultural practices in Denmark, and (2) map the existing governance mechanisms relevant to environmental sustainability of agricultural crop production in Denmark for the end-uses of solid and liquid biofuel production. The study was carried out in a broader European Union and bioeconomy context, as the Danish bioenergy and biofuel governance landscape is inseparable from these.

Methods

In pursuit of the aims described above, we

1. Give an overview of agricultural land use and crop production in Denmark through time,
2. Review selected environmental impacts associated with agricultural crop and livestock production in Denmark, focusing on greenhouse gas emissions, soil carbon, water and biodiversity, and
3. Describe the development of the governance complex relevant to the selected sustainability issues, including the involved actors, with the purpose to identify drivers of sustainability governance development.

For the purpose of this study, we define governance comprehensively to include governmental regulation, international agreements and conventions, public or private certification systems, co-regulation between public regulation and private certification, and standardisation [13].

Agents of the governance complex around agricultural production with energy ends are identified and classified according to the governance triangle [14]. The classification identifies seven categories of governance agents based on different degrees of involvement of states, NGOs and firms. Here states mean a jurisdiction, which can be nation states or supranational legislative bodies, e.g. the EU.

Based on publicly available databases, inventory reports and scientific literature, the existing governance measures are evaluated for their effectiveness in addressing GHG emissions, soil carbon, water quality and biodiversity.

Results and discussion

Land use

The Danish landscape is dominated by agriculture. In 2016 62% of the land area was classified as agriculture; 15% as forest; 14% as urban areas, infrastructure and other artificial surfaces; and 9% as open nature. Correspondingly, 43% of the land area was agriculture and 38% forest land in the EU28 [15].

Between 1961 and 2016 the agricultural area has decreased from 3.2 to 2.6 million ha, corresponding to an annual loss of 0.35%. Agricultural land losses comprise mainly arable land, as well as permanent meadows and pastureland. A similar development is seen in the EU with an annual loss of agricultural land of 0.28% [15]. A main driver of land use change in the EU, from agriculture to other land uses, is urban development and infrastructure [16], but also a decline in landscape quality is observed driven by agricultural intensification, economic development and intended as well as unintended effects of EU policy [17].

A significant part of the agricultural land in Denmark, and in the EU, is allocated to cereal production [15]. There has been a slight decrease over time, with a similar increase in land allocated to oil crops. The bioeconomy is not identified as an individual sector in national and EU statistics and cannot be unambiguously separated from other economic sectors. Industrial crops cover a variety of crops that are not traditionally grown for human consumption without considerable processing, e.g. rape seed and sunflower that are used for vegetable oil production, and hemp and cotton used for fibre production. Denmark and the EU have experienced an increase in the agricultural area covered with industrial crops in the same period where the agricultural area has decreased. One purpose of some industrial crops (e.g. oil crops) is liquid biofuel production, and both Denmark (Fig. 1b) and the EU (Fig. 1c) have seen a development in production over time. In the EU, biodiesel and biogasoline production has generally increased since 1990. Biodiesel production in Denmark is also at a higher level currently than in 1990 but may have peaked at the end of the first decade of the 2000s.

Biodiesel is the main liquid biofuel produced and is typically produced from rapeseed [19]. Biogasoline (bioethanol, biomethanol, biobutanol, bio ETBE and bio MTBE) is typically produced from sugar beet, sweet sorghum and maize [19].

Agricultural waste streams and by-products are to some extent used for the production of liquid biofuels [20] and gaseous fuels, as well as heat and electricity. In Denmark the use of cereal straw for heat and electricity production has been a commercial supply chain for decades [12] and the consumption has increased from 13 PJ in 1990 to 20 PJ in 2017 (Fig. 1a). Also, in some other EU member states, residues are used for energy production. Depending on local crop production, the residue feedstock can be straw, husks, ground nut shells, olive pomace and other wastes from maintenance, cropping and processing of plants [18].

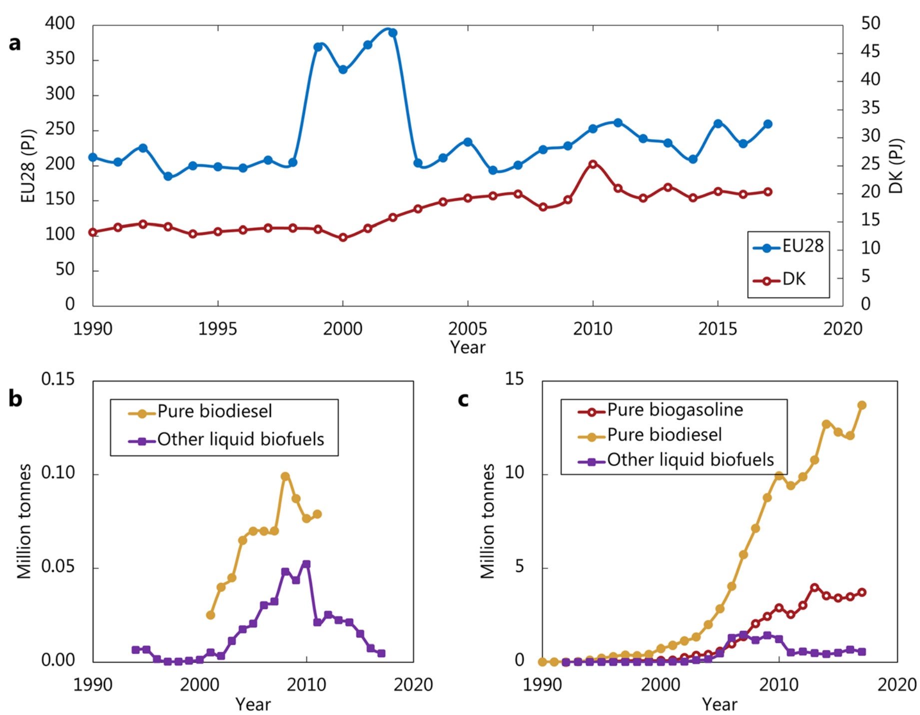

Fig. 1 a Other vegetal material and residues (SIEC code 5150) harvested and used for energy production in Denmark and the EU from 1990 to 2017. Other vegetal material and residues covers solid biofuels as straw, husks, nut shells, prunings, olive pomace and other wastes from the maintenance, cropping and processing of plants. **b** Production of liquid biofuels (SIEC code 5210, 5220 and 5291) in Denmark and **c** in the EU28 from 1990 to 2017. Based on data from Eurostat [18]

Environmental impacts of agricultural production

The array of sustainability issues relevant to agricultural production covers a large number of environmental, economic and social impacts. This study focuses on environmental impacts of high concern in Denmark and the EU; greenhouse gas emissions, soil organic matter, water quality and biodiversity. After World War II, new technological opportunities had a large impact on the development of agriculture in Europe, which carried environmental impacts on agricultural lands and adjacent ecosystems. Tractors replaced horses, herbicides replaced soil scarification, and commercial mineral fertilisers replaced manure. This laid the ground for specialised farms and intensive agriculture, where animal husbandry and crop production did not necessarily depend on each other.

Greenhouse gas emissions

GHG emissions from the agricultural sector are reported annually through the national emission inventory submitted under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (KP). In 2016, the agricultural sector accounted for 21% of Denmark's total GHG emissions (land use, land use change and forestry (LULUCF) not included). Emissions have decreased 17% since 1990 (Fig. 2a). In 2016, the GHG emissions from the agricultural sector were CH_4, 5.56 Mt CO_2eq year^{-1}; N_2O, 4.76 Mt CO_2eq year^{-1}, CO_2, 0.22 Mt year^{-1} for a total of 10.53 Mt CO_2eq year^{-1}. This corresponds to 39% for agricultural soils, 36% for enteric fermentation and 23% for manure management [21]. Manure management covers all operations related to handling, storage and transport of manure. Methane emissions are mainly related to livestock production. While methane emissions from enteric fermentation have decreased 8% since 1990, from 161.6 to 148.9 kt CH_4 year^{-1}, emissions from manure management have increased almost 20%, from 61.8 to 73.8 kt CH_4 year^{-1}. Emissions from enteric fermentation have declined with the number of dairy cattle, and emissions from manure management have increased because of changes in livestock housing systems [21]. Nitrous oxide emissions have decreased 27% since 1990, from 21.7 to 16.1 kt N_2O year^{-1} due to measures taken to reduce leaching of nitrogen from agriculture to the aquatic environment, to improve manure management and reduce the use of synthetic fertilisers [21].

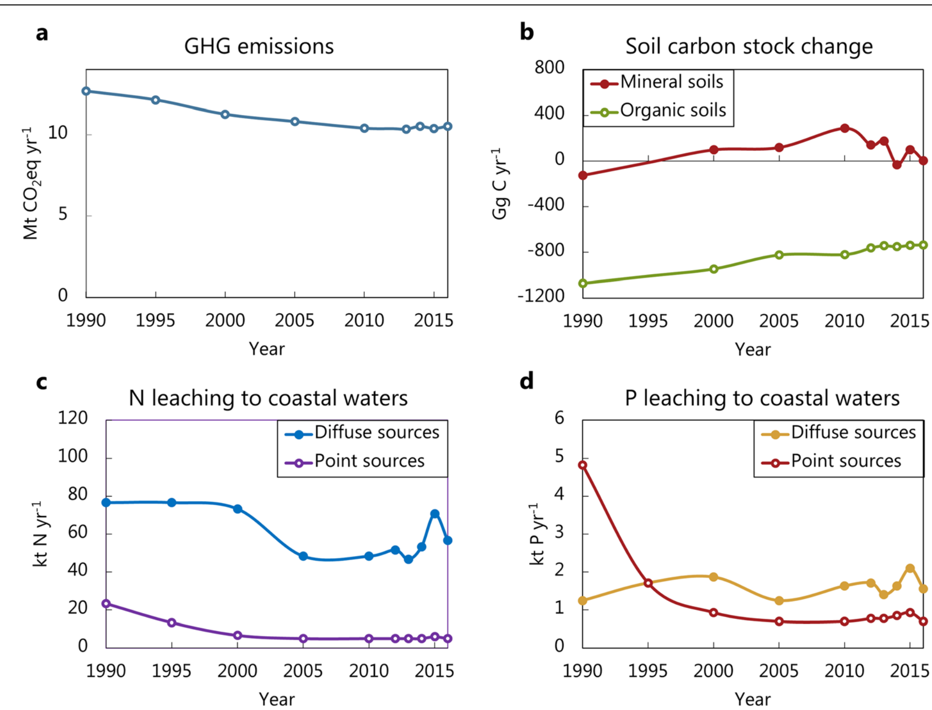

Fig. 2 a Greenhouse gas emissions from the agricultural sector in Denmark from 1990 to 2016 based on national emission inventory reporting to the UNFCCC and the Kyoto Protocol [21]. **b** Change in Danish cropland soil carbon stock from 1990 to 2016 based on national emission inventory reporting to the UNFCCC and the Kyoto Protocol [21]. **c** Nitrogen leaching from diffuse sources (primary agriculture) and point sources (wastewater treatment and industry) to coastal water bodies in Denmark from 1990 to 2016. **d** Phosphorus from diffuse sources (primary agriculture) and point sources (wastewater treatment and industry) to coastal water bodies in Denmark from 1990 to 2016. **c** and **d** are adopted from national reporting to the EU water framework directive [22]. An unusually large rainfall in 2015 can explain the peak in diffuse N and P leaching that year

Soil organic carbon

According to the national emission inventory submitted under the UNFCCC and the KP [21], croplands contributed 6% of the total Danish GHG emission in 2016, mainly due to cultivation of a large proportion of organic soils (Fig. 2b). Since 1990, GHG emissions from croplands have declined 23%. Agriculture manages approximately 70% of the Danish soil organic carbon (SOC) pool [23]. In the last 2–3 decades, carbon has been lost from agricultural soils at an average rate of 0.2 MgC ha^{-1} $year^{-1}$ [24]. SOC loss is mainly seen from organic loamy soils, while the coarser soils have sequestered carbon. This is due to agronomic practices and management that influence input and accumulation of soil carbon. Perennial grass crops, autumn sown cereal crops and the use of livestock manure tend to be beneficial to soil carbon accumulation [24]. Harvesting crop residues for fodder, bedding and energy contributes to the loss of SOC in a complex interaction between crop type, soil type, climate, management and the soil depth surveyed [25–27]. Straw harvest from spring sown cereals tends to contribute to a larger SOC loss than straw harvested from autumn sown cereals [25], probably caused by the higher yield of autumn sown crops. The higher amounts of root, stubble and leaf biomass sustain SOC levels [28]. Soil carbon loss is not only a climate change concern. Soil fertility is influenced by soil carbon, and increased straw harvest rates may have implications for soil organic matter contents and other soil quality indicators [29, 30]. In a soil fertility perspective, leaving a certain amount of residues in the field is beneficial to maintain the soil's structural stability, infiltration capacity and microbiological activity [31].

Water and water quality

Even if the nitrogen discharge from all sources has decreased in recent decades, the impact of agricultural fertilisation on nitrate concentrations in ground and surface waters is one of the largest concerns in Denmark [22]. Diffuse discharge contributes 90% of the total discharge of nitrogen to the ocean, and agriculture is the primary contributor to diffuse discharge (Fig. 2c). Over time, there is a clear correlation between the excess nitrogen and nitrate concentrations in the groundwater, which are now generally below the EU drinking water limit of 50 mg nitrate per litre. The nitrogen balance of Danish agriculture as a whole has declined 35% from a surplus of 400,000 tonnes in 1990 to 260,000 tonnes in 2016, mainly driven by higher utilisation of manure and reduced use of mineral fertilisers [22]. Phosphorous discharge to surface waters has shown similar developments, with a reduction from 6000 tonnes in 1990 to 2300 in 2016 (Fig. 2d). The reductions mainly took place before the turn of the millennium and mainly through initiatives in wastewater treatment and industry (point sources). In 1990, point sources contributed 90% of phosphorous discharges. In 2016 the contribution had dropped to 30% [22].

Biodiversity

Biodiversity in general is under pressure from human activity [32] and climate change [33]. The most frequently reported pressures and threats for species in Europe are associated primarily with changes in hydrology and agriculture [34]. In Denmark, agriculture, infrastructure and the built environment are the most intensively used land cover classes, which also accommodate the smallest share of threatened species [35]. Historically, agriculture has had an important role in supporting some types of biodiversity, but changed and intensified management (chemical pest control, mineral fertilisation, crop rotation) and structures (larger farms, larger fields) have changed the diversity of the agricultural landscape [36] and increased the pressure on biodiversity. An assessment of the status of Danish biodiversity covering 139 biodiversity elements (65 species/species groups, 43 habitats and 31 processes) in nine ecosystems found that overall 47% of the elements are in decline. For agricultural lands, 53% of the elements are in decline. Most species surveyed (birds, insects, mammals and plants) are in decline, particularly bees [35].

Governance

In the following, we characterise governance measures according to the governance triangle (Fig. 3) and analyse the different measures' effectiveness in addressing GHG emissions, soil organic matter, water quality and biodiversity. The governance triangle is a systematic classification of regulatory actors. The triangle depicts the regulatory space and diversity of regulatory institutions [14]. Here the triangle defines the direct participation of states or supranational governance bodies (e.g. EU), firms and non-governmental organisations (NGOs).

GHG emissions

This section describes the GHG emissions from agriculture in the form of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). CH_4 emissions originate from enteric fermentation in livestock production and manure management. N_2O emissions are from manure management and from agricultural soils. Additionally, there are some minor emissions of CH_4 and N_2O from burning of straw on fields. CO_2 emissions from agriculture concern emissions from liming, urea application and use of inorganic fertilisers. CO_2 uptake and emissions from agricultural soils are not counted as agricultural emissions, but are included in

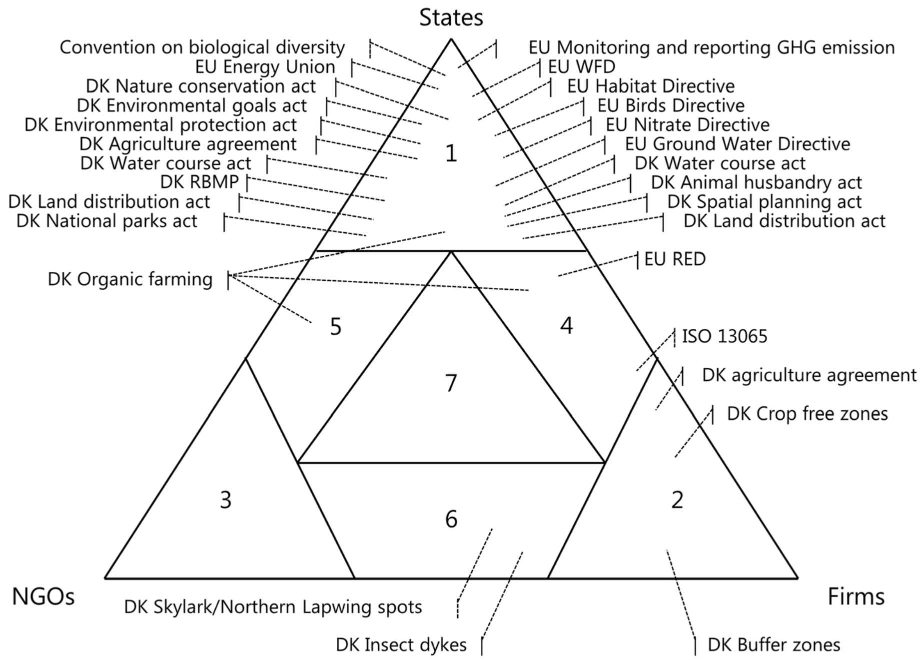

Fig. 3 The governance triangle and classification of regulation governing agricultural biomass production for bioenergy and biomaterials. The seven categories include (1) traditional top-down legal standards, typically laws, (2) self-regulation, (3) third-party private regulation, (4) standards of firms influenced by states (co-regulation), (5) standards of NGOs influenced by states (co-regulation), (6) joint efforts between firms and NGOs, (7) joint efforts between firms, NGOs, and States (transnational regulation). Adopted from [14]. RBMP, River Basin Management Plans; WFD, Water Framework Directive; RED, Renewable Energy Directive

the LULUCF-sector according to UNFCCC inventory guidelines [21].

There are other ways to define GHG-emissions from agriculture. Dalgaard et al. [37] chose to include changes in soil carbon pools as well as fossil energy use in their assessment and argue that agriculture also can provide products that can substitute for fossil fuels in other sectors. Hermansen and Olesen [38] argue that you can also choose a life-cycle or consumption-based perspective and include emissions from feed produced outside Denmark. In this analysis, we focus on GHG emission reported according to UNFCCC guidelines as governance instruments and compliance is gauged against these.

In Denmark, the GHG emissions from agriculture are governed along with GHG emissions from forestry, transport (excluding aviation and shipping) and buildings, the so-called non-ETS sector (ETS is the European Union Emission Trading System). The GHG emission reduction target from these sectors is decided by the EU, and individual member states' contributions are laid down in an effort sharing decision. Denmark's target is an emission reduction of 20% by 2020 compared with 2005 [39]. From 2021 to 2030, Denmark's share is 39% compared with 2005. The Danish share in both time periods is among the highest in the EU. All member states are individually responsible for implementing EU directives in national legislation. Additionally, the Danish Parliament has in 2014 adopted a climate act with the purpose of establishing a strategic framework for Danish climate policy in order to convert Denmark into a low-emission society by 2050 [40]. A political agreement from 2018 goes a step further with the aim of achieving net zero emissions by 2050 [41].

There is no direct or targeted legislation of GHG emissions from Danish agriculture. One notable exception is anaerobic digestion (biogas) which has a long history in Denmark. The energy production from biogas that can replace natural gas is part of the ETS sector, whereas emissions from manure management (CH_4 and N_2O) are attributed to agriculture. Measures targeting anaerobic digestion will therefore influence both the emissions from agriculture (non-ETS) and energy-related emissions (ETS sector). Governance of anaerobic digestion in Denmark has recently been thoroughly reviewed by Bangalore et al. [42] and Al Saedi et al. [43]. They find that Denmark has introduced several policy measures (type 1) since 1988, most notably in the form of feed-in-tariffs and other subsidies, but also schemes to address climate and sustainability concerns. These measures include limiting the share of energy crops to be used for biogas production and measuring methane losses from digesters and upgrading facilities [43, 44].

Soil carbon

At the EU level, the governance of soil health, soil quality and soil carbon is fragmented and soil issues are imbedded in various policy frameworks [45]. Building on the EU soil thematic strategy of 2006, a soil framework directive was proposed, but due to opposition from five member states the proposal was withdrawn in 2014 [46]. Carbon in agricultural soils is addressed in various forms in 16 EU regulations, directives, decisions and communications within the Common Agricultural Policy (CAP), climate policies, nature conservation policies, environmental policies and communications from the European Commission [47].

The CAP (type 1) has a number of instruments that directly or indirectly address soil carbon. *Cross-compliance* is a compulsory mechanism linking most payments under the CAP to a set of standards to ensure good agricultural and environmental conditions of land (GAECs) and statutory management requirements (SMRs). GAEC 6: "Maintenance of soil organic matter…" directly aims to ensure that soil carbon levels are maintained. GAEC 4: "Minimum soil cover" intends to reduce soil erosion, but indirectly also ensures conditions beneficial to maintain soil carbon. With the 2013 reform of the CAP, an instrument termed *Greening* was introduced as a new type of direct payment to farmers. Greening was intended to increase the environmental performance of the CAP. The instrument is also compulsory and includes three agricultural practices, which are meant to benefit the environment and climate; one of them directly addressing soil carbon, "maintenance of permanent grasslands". Preservation of grasslands conserves soil carbon [48] and protects grassland habitats [49]. A ratio of permanent grassland to agricultural land is set and monitored by member states at national or regional level. "Environmental measures under rural development" is a voluntary mechanism including additional payments to reward farmer for certain practices that benefit the environment and climate. Regulation on organic farming is part of the CAP but includes various governance measures that can be characterised as co-regulation between states and firms (type 4) and between state and NGOs (type 5). This regulation is relevant for all four aspects of environmental sustainability treated here.

With reference to the use of agricultural biomass for energy purposes, article 17.5 in the EU-RED (type 4) states that [50]: "Biofuels and bioliquids taken into account for the purposes referred to in points (a), (b) and (c) of paragraph 1 shall not be made from raw material obtained from land that was peatland in January 2008, unless evidence is provided that the cultivation and harvesting of that raw material does not involve drainage of previously undrained soil" effectively protecting soil carbon by excluding biomass from parts of agricultural lands both within and outside the EU.

In addition, the voluntary ISO (type 4) standard 13065 addresses carbon in soil in its principle to "protect soil quality and productivity". Indicator 5.2.3.1.1 requires the economic operator to describe procedures to identify potential impacts on soil quality and productivity, including consideration for e.g. organic carbon in soil [51].

Water quality

Denmark, with 62% of the area in mostly highly intensive and livestock dense agriculture, has historically been a major supplier of food for export. During the twentieth century, there has been large and increasing nitrogen (N) surpluses and high leaching of N to the groundwater. Combined with a long coast line and shallow estuaries, this has led to environmental issues with eutrophication and water quality [52]. This resulted in a political focus on mitigating losses of N and other nutrients to the aquatic environment from the 1980s and onwards. Several action plans and initiatives (type 1) have been implemented during the last three decades to address these issues (Table 1).

The overall aim of these plans has been to reduce the nutrient leaching from diffuse sources as well as discharges

Table 1 Action plan and initiatives implemented to protect water quality and the aquatic environment. Adapted from [52–54]

Year	National regulation	EU regulation
1985	Action Plan on nitrogen, phosphorus and organic matter (NPo)	
1987	Action Plan for the Aquatic Environment I (API)	
1991	Action Plan for Sustainable Agriculture	Nitrates Directive (1991/696/EC)
1998	Action Plan for the Aquatic Environment II (APII)	
2000		Water Framework Directive (2000/60/EC)
2001	Ammonia Action Plan	
2004	Action Plan for the Aquatic Environment III(APIII)	
2006		Ground Water directive (2006/118/EF)
2009	Green Growth Plan	
2011	River Basin Management Plans, implementing the EU Water Framework Directive	
2016	Agriculture Agreement	

from point sources for both N and P through improved nutrient management and wastewater treatment [53, 55].

The action plans have utilised different measures to achieve the goals laid out in them, e.g. maximum livestock density, mandatory crop rotation and fertiliser plans, norms for nitrogen application for specific crops, fertilisation below economic optimum, mandatory catch crops, subsidies to low input agriculture, requirements for manure handling and animal housing and buffer zones [52, 54, 55]. These measures have been reviewed and categorised according to type of regulation (command and control, market-based and information and voluntary action as well as input/output regulation) in Dalgaard et al. [52]. Their results show that command and control measures were implemented initially and were followed by market-based and voluntary actions.

Denmark has implemented the EU Water Framework Directive (2000/60/EC) [56], Nitrates Directive (1991/696/EC) [57] and Ground Water Directive (2006/118/EF) [58] in its national legislation through several action plans and through the River Basin Management Plans of the Water Framework Directive [52]. The River Basin Management Plans set out targets for individual water bodies. The first was adopted in 2014 and the second in 2016. The overall aim of the Water Framework Directive is to ensure "good status" of all water bodies in the EU before 2015 [59].

During the last 30 years, there has been a clear development in the type of legislation regarding water quality in Denmark. The early action plans had general regulation with equal norms and standards for the entire country. Since then there has been an increasing focus on targeted regulation and at the same time an increased focus on regulating the output of nutrients. This can be exemplified by the River Basin Management Plans that regulate individual water bodies by applying a limit of output of N to that water body. This differs from the early action plans that for instance set a maximum livestock density for the entire country through command and control measures [52, 53]. Similarly, the most recent action plan (Agriculture Agreement from 2016) applies less national N regulation and more locally targeted measures and voluntary action (type 2) [55].

Biodiversity

The strictest type of natural area protection in Denmark was introduced by law in 1917. This type of protection is carried out for the purposes contained in the Nature Conservation Act, including protection of landscapes, animals and plants and their habitats, cultural history, natural history and educational values. The protection may lay down rules for the improvement and restoration of the area, and it may regulate people's access to the area. The owner's future use of the protected areas is often significantly restricted, with full or partial abandonment of rights and economic compensation for the loss [60]. Since the early 1990s, Denmark's goals for conservation of biological diversity have been set in the context of the United Nations' (UN) and the EU's frameworks for conservation of biological diversity. Parties to the UN have agreed on the "Strategic Plan for Biodiversity, including the Aichi Biodiversity Targets, for the 2011-2020 period", under the Convention for Biological Diversity (CBD) [61]. The Aichi agreement includes 20 specific targets under five more general strategic goals [62]. Target seven stipulates that "by 2020, areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity". The Aichi targets are also the backbone of the "The EU Biodiversity Strategy to 2020" [63, 64], which includes six goals for biodiversity. Goal three concerns the increased contributions of agriculture and forestry to maintaining and enhancing biodiversity, while goal two emphasises the need for green infrastructure (GI). GI should aim at reconnecting the highly fragmented natural areas in the European Union and improve their functional connectivity.

The EU Biodiversity Strategy is being implemented through legislation under the umbrella of "Natura 2000" [65]. Natura 2000 includes two main legislations, the Birds Directive, which was first adopted in 1979 (79/409/EEC) and revised in 2009 (2009/147/EC), and the Habitats Directive from 1992 (92/43/EEC), which stipules protection of habitat types, wild animals and plants that are characteristic, rare or threatened within the EU. The two directives require identification and appointment of a set of protected areas. The so-called Special Protection Areas (SPA) under the Birds Directive, and Sites of Community Importance (SCI) and Special Areas of Conservation (SAC) under the Habitats Directive are together called Natura 2000 areas. The Birds Directive addresses more than 170 species or sub-species, of which 80 are found in Denmark. The Habitats Directive includes more than 200 natural habitat types and 700 animal and plant species. Of these, about 60 and more than 100, respectively, can be found in Denmark [66].

As a signatory to the CBD, Denmark must elaborate, adopt and implement a national biodiversity strategy. Accordingly, the government's strategy was outlined in the Danish Biodiversity Strategy 2014–2020 [67]. The strategy includes 22 initiatives under three focus areas: (1) more and better interconnected nature, (2) strengthened initiatives for wild animals and plants, and (3) improved sense of community through nature experiences and outdoor activities. The initiatives cover most of the Aichi targets and the six EU priorities. The Danish efforts are contained within various legislations that largely implement EU legislation. The Natura 2000 areas are the backbone of the national Danish biodiversity conservation efforts, as implemented through the Nature

Conservation Act, the Environmental Goals Act and the Forest Act, with associated ordinances and national and EU level guidelines that specify and explain the intent of the laws. The Nature Conservation Act of 1992 implements EU legislation with early provisions of the Nature Conservation Act of 1972, to address the so-called §3 areas, which are protected wherever they occur in Denmark [68]. About 10% of Denmark's area is protected under this §3. Additional legislation contributes to nature conservation in Denmark in various ways, in particular the Environmental Protection Act, the Water Course Act, the Animal Husbandry Act, the Spatial Planning Act, the Land Distribution Act and the National Parks Act [69], again, with associated ordinances and guidelines.

Some of the Natura 2000 and §3 protected areas are located on agricultural lands, with farmers also making contributions to nature conservation and biological diversity through planting of hedges and windbreaks, establishment of small biotopes for the benefit of plant and animal life, and new water holes for the benefit of amphibians. Several subsidies are offered by the Government under the Rural Development Program for the purpose of such management.

Nature protection according to the Animal Husbandry Act is based on mapping of three categories of natural areas. Category 1 covers ammonia-sensitive natural areas, as well as heathland and biodiversity commons within the Natura 2000 areas. Category 2 includes ammonia-sensitive natural areas outside the Natura 2000 areas. Category 3 includes potentially ammonia-sensitive natural areas protected as §3 areas.

The Water Course Act requires a 2-m wide buffer zone around natural watercourses and lakes, and artificial watercourses that are classified as having "good ecological potential" or "maximum ecological potential" based on the Environmental Goals Act [70]. The ecological condition is determined from biological, chemical and hydromorphic criteria, with an assessment of the biological condition being based on the so-called Danish water course fauna index (DVFI), which assesses the presence of small faunal groups [71, 72]. In the buffer zone, soil preparation, planting and changes to the terrain are prohibited.

Considering the very fragmented European and Danish landscapes, the focus on green infrastructure is important. The Danish Spatial Planning Act from 1992 includes an obligation for the municipalities to designate and formulate guidelines for the administration of valuable nature areas and ecological corridors and networks, as well as the Green Map of Denmark. In addition, the Land Distribution Act from 2005 has as one of its aims to optimise the network of different land uses to protect and improve natural and environmental values in the landscape.

To the extent that agricultural crop produce is used for bioliquids, including transportation biofuels, the EU Renewable Energy Directive also stipulates that the biomass raw material shall not be obtained from land with high biodiversity value, including specific types of forest, grasslands and areas designated for nature protection, and specific ecosystems or species protected by law or international agreements [73]. This also concerns raw materials from land converted from such natural area types after 1 January 2008.

The governance that regulates biodiversity in the Danish landscape including agricultural areas is mostly governmental (type 1), but other types exist such as crop free zones inside fields, skylark or Northern lapwing spots and insect dykes [74], and subsidies for voluntary environmentally benign management options, e.g. grassland, wetlands and fallowing [75] (type 2). Some of these measures can be in cooperation with or by recommendation from an NGO (type 6) [76, 77]. Policy measures vary from command and control with or without compensation, to financially incentivising and voluntary measures. A movement towards voluntary measures has especially been seen for fresh water biodiversity as also addressed by water regulations [52].

A set of indicators are used to monitor progress and fulfilment of the biodiversity goals in Denmark. The indicators take a starting point in the EU SEBI indicators, which were created in the "Streamlining European 2010 Biodiversity Indicators" process. The purpose of the process was to examine and report progress towards the EU and CBD goals [78]. A number of UN and EU organisations launched the SEBI in 2005, aiming at producing and developing consistency across global, regional, EU and national biodiversity indicators. In 2007, a set of 26 indicators were published [79]. The SEBI monitors biodiversity in five perspectives: (1) status and trends of the components of biological diversity, (2) threats to biodiversity, (3) ecosystem integrity and ecosystem goods and services, (4) sustainable use, and (5) access and benefits sharing, resource transfer and use, and public opinion and awareness.

Indicators for a more streamlined monitoring have been developed, and the process to improve monitoring continues. Statistics and interactive maps of protected areas are increasingly available at both EU and national levels.

Effectiveness

GHG emissions

From 1990 to 2016, there has been a 17% reduction in emissions of GHGs from agriculture. From 12.76 Mt CO_2eq year^{-1} in 1990 to 10.53 Mt CO_2eq year^{-1} in 2016 [21]. A number of changes in farming practices have reduced the emissions, especially of N_2O. A ban on burning straw on fields reduced the need for liming of fields, and several action plans for the aquatic environment have improved N management and reduced losses of nitrogen (see Water Quality) [37]. This shows that legislation primarily put in place to improve water quality and reduce nutrient losses has had the largest effect in reducing the GHG emissions from agriculture.

The Danish Council on Climate Change recently concluded that Denmark will meet its non-ETS 20% emission reduction target for 2020 [21, 80]. A similar conclusion was reached by the Danish minister of Energy, Utilities and Climate in his report to the Danish Parliament, whereas it is more uncertain whether Denmark will live up to the 39% reduction target for 2030. It depends on additional initiatives in the non-ETS sectors, i.e. agriculture, housing and transport [81].

Soil carbon

The European Court of Auditors (ECA) evaluated the CAP Greening mechanism [82] and found that, as currently implemented, it is unlikely to increase the environmental and climate performance of the CAP. According to the ECA, Greening remains in essence an income support scheme with a significant policy deadweight[1]. ECA estimates that farming practices have changed on around 5% of EU agricultural land due to the Greening mechanism, an impact that does not match the complexity that Greening has added to the CAP [82]. Also the fact that Cross-compliance and Greening rather than being complementary instruments are competing, limits the potential environmental ambitions of the CAP reform [83]. Although loss of soil organic matter is addressed in several EU policies in addition to Greening, the fragmentation of soil issues in policies limits the effectiveness of soil organic carbon governance [84].

The component of co-regulation (voluntary schemes for documentation and verification of biofuel's sustainability recognised by the European Commission) in the Renewable Energy Directive (RED) is assessed as a weakness to govern sustainability as not all recognised schemes cover important aspects to ensure sustainability, the recognition procedures have not been reliable, some schemes do not have appropriate verification procedures, and transparency is lacking in some schemes [85]. The European Court of Auditors [85] recommends that the European Commission should carry out more comprehensive assessment of voluntary schemes to ensure e.g. compliance with the regulation and evidence of the origin of waste and residues used for biofuels. Furthermore, the European Commission should ensure that voluntary schemes' governance reduces the risk of conflicting interests and remains transparent. More generally, it has been suggested that current and future policies and governance measures do not sufficiently stimulate large-scale soil carbon projects because of structural flaws in the measures [86]. One suggestion is to include agriculture in the EU ETS allowing regulated industries to buy offsets from the agricultural sector [86].

Water quality

A comprehensive Danish water and nature monitoring programme was established in 1988. This monitoring programme makes it possible to evaluate the effectiveness of the water quality regulation as it has been in place during the time of the action plans [54]. It is outside the scope of this article to evaluate the development of every water quality indicator, but the legislation has been successful for the most part. Losses of nutrients from both point and diffuse sources to water bodies have generally been reduced during the last ~ 30 years: less nitrate in groundwater [55], reduced N and P load to coastal waters [53], lower N leaching from the root zone [52, 54], decreasing national N and P surpluses [53]. A recent relaxation on fertiliser norms has, however, led to increased leaching of nitrogen from agricultural soils (Fig. 2c).

All of this was achieved while agricultural production in Denmark increased. The cost of reducing N-losses has increased over time, and it has become more difficult to achieve cost-effective reductions with general regulations [52]. This has led several researchers to emphasise and suggest a holistic, output-based and targeted local regulation, which is also the intent of the Danish Agriculture Agreement from 2016 and the River Basin Management Plans [52–54].

It is outside the scope of this study to go into great detail with the effectiveness of the River Basin Management Plans and the ecological condition of all Danish water bodies, but presently there is no type of water body (e.g. groundwater, streams) where the majority would be in good ecological condition going into the second plan period [87].

Biodiversity

As agreed in 1992 in the Earth Summit in Rio, the goals of the CBD to halt decline of international and national biodiversity were originally planned to be fulfilled by 2010. For the EU as a whole, the goals were generally not fulfilled [88]. The monitoring of open lands connected to agricultural activities in Denmark shows a similar pattern.

The presence of farmland birds has declined by about 30% in the last 30 years, and the number of hares has been in decline since the 1960s. However, a close examination by Fox [89] showed that a specific set of Danish farmland bird species has largely maintained its population level since the

[1]A situation, where a subsidised activity or project would have been wholly or partly undertaken anyway.

1980s. He ascribes this to the Danish agri-environmental policies relying on a relatively good scientific understanding of the mechanisms that enable farmland birds to maintain population levels in the face of continued agricultural changes, and emphasises that this is a lesson learned.

The genetic diversity of domestic animal husbandry breeds has been in decline, even if this indicator shows some improvement.

One of the key threats to biodiversity is the excess nitrogen and phosphorus from agriculture and some improvement has been achieved in recent decades, but after increasing the fertilisation norms and introducing more voluntary regulation in recent years, the nitrate levels in waters have increased again.

The area with organic farming has increased significantly in the last 20 years, despite a temporary decline in 2006–2007.

Many animals and plants covered by the EU Habitats Directive are not in good condition, with 48% of the 70 species to be protected having an unfavourable conservation status, and the situation is the same for many of the habitats; about 59% of the 58 habitats to be protected have been assessed with an unfavourable conservation status.

The area of open vegetation with high biodiversity value has declined from 25% around 1920 to about 10% in 2000. The open lands have a distinct "small-scale landscape" character with fragmented nature. About 85% of the areas with open vegetation are smaller than 5 ha. Additionally, there are small biotopes that are not registered, such as fences, water holes, bogs, marl excavation areas and bronze age-burial mounds. A preliminary estimate is that these small biotopes have declined from 1–6% in the late 1990s to less than 2% at present. Even if the §3 natural areas are generally well protected, it remains a challenge that about 92% are smaller than 5 ha, and 58% are even smaller than 0.25 ha (mainly lakes and water holes).

The number of new strict protections has declined in the last 30–40 years, mainly due to the implementation of planning laws, the §3 protection and other legal measures.

There are signs of policies showing some effectiveness, e.g. for the threats posed by excess nutrients from agriculture [52] and selected farm bird species [89]. However, severe challenges persist for the protection of biodiversity associated with and impacted by agricultural activity [35].

Conclusions

In this analysis we evaluated governance measures and their effectiveness in addressing the sustainability of agricultural production of biomass for energy purposes. Sustainability issues were represented by greenhouse gas emissions, carbon in soil, water quality and biodiversity.

Most governance measures can be characterised as type 1 regulation according to the governance triangle, that is state-level or supranational regulation. Some examples of co-regulation (types 4, 5, 6) and voluntary initiatives (type 2) were also found.

The sustainability of agricultural biomass for bioenergy or biomaterials is not always governed independently. Type 1 governance instruments focus on land and land management irrespective of the end-use of the crop. EU-RED and the ISO 13065 standard (type 4) take the opposite view and address sustainability from the point of view of the end-use irrespective of the origin of the biomass. Biogas production is an exception with several type 1 policy measures, e.g. subsidies and schemes that address climate and sustainability concerns.

Greenhouse gas emissions from agriculture is a virtually unregulated field, and although emissions have declined, partly as a co-benefit of regulation of other environmental issues, additional regulation for Denmark is required to live up to its 2030 emission reduction target in the non-ETS sector in which agriculture belongs.

Carbon is lost from agricultural soils, and although the loss has declined 23% since 1990, significant amounts of carbon are emitted as CO_2 to the atmosphere from cultivation of organic soils. Soil carbon is governed by predominantly mandatory state regulation (type 1), but voluntary co-regulation (type 4) also plays a role. The regulatory framework is criticised for its complexity, its competing instruments and its recognition procedures of voluntary co-regulation.

Water quality is mainly governed by national and supranational type 1 regulation, and this analysis finds that the governance measures in place have improved water quality during the last three decades, but it has still been difficult to achieve the ambitious goals of the Water Framework Directive.

Most biodiversity in Denmark is associated with forests and protected nature areas, while it remains a challenge to promote such values in agriculture. Very little is known about biodiversity values in agricultural lands, and it will probably remain a challenge to prioritise this parameter in intensely used landscapes such as in Denmark. Biodiversity is mainly governed by national and supranational type 1 regulation together with types 2, 4, 5 and 6. However, biodiversity is a complex parameter and it continues to be discussed if the regulations have led to any improvement. This threatens the legitimacy of the legislation, as the affected private actors, mainly in forestry, are faced with costs related to regulations, which are not compensated by the state.

The Danish case is an important example of how environmental sustainability has been addressed in an intensively managed country with a high proportion of agricultural land. The challenges are large, and while some success has been achieved in addressing water quality challenges, initially with national uniform regulation and later with local initiatives, the biodiversity challenges are far from being solved. In a future with an expected higher pressure on natural resources driven by population growth, economic growth and a growing bioeconomy, it is paramount to develop governance mechanisms and management regimes to ensure sustainable land management. Sustainable intensification of agriculture is one option [90], but a holistic approach is required.

Abbreviations

AP: Action Plan on water environment; CAP: European Union Common Agricultural Policy; CBD: Convention for Biological Diversity; DVFI: Danish water course fauna index; ECA: European Court of Auditors; ETBE: *Ethyl tert-butyl ether*; ETS: European Union Emission Trading System; EU: European Union; GAEC: Good agricultural and environmental conditions; GHG: Greenhouse gases; ISO: International Organization for Standardization; KP: Kyoto Protocol; LULUCF: Land use, land use change and forestry; MTBE: *Methyl tert-butyl ether*; NGO: Non-governmental organisation; NPo: Action Plan on nitrogen, phosphorus and organic matter; RBMP: River Basin Management Plan; RED: Renewable Energy Directive; SAC: Special Areas of Conservation under the Habitats Directive; SCI: Sites of Community Importance under the Habitats Directive; SDG: Sustainable Development Goals; SEBI: Streamlining European Biodiversity Indicators; SMR: Statutory management requirements; SOC: Soil organic carbon; SPA: Special Protection Areas under the Birds Directive; UN: United Nations; UNFCCC: United Nations Framework Convention on Climate Change; WFD: Water Framework Directive

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Authors' contributions

NSB and IS devised the project. NSB, SL and IS conducted the analyses and authored the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All material and data used in this analysis is publicly available.

Ethics approval and consent to participate

No ethical issues pertain to this analysis.

Consent for publication

All authors have approved the manuscript.

Competing interests

NSB and IS declare no competing interests. SL is employed by Danish Energy; a non-profit association of Danish energy companies, some of which are commercially involved in different parts of the Danish bioeconomy.

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